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METHODOLOGY • ALLOCATION ISSUES • CASE STUDY

Allocation issues in LCA methodology: a case study of corn stover-based fuel ethanol

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Abstract

Background, aim, and scope Facing the threat of oil depletion and climate change, a shift from fossil resources to renewables is ongoing to secure long-term low carbon energy supplies. In view of the carbon dioxide reduction targets agreed upon in the Kyoto protocol, bioethanol has become an attractive option for one energy application, as transport fuel. Many studies on the LCA of fuel ethanol have been conducted, and the results vary to a large extent. In most of these studies, only one type of allocation is applied. However, the effect of allocation on outcomes is of crucial importance to LCA as a decision supporting tool. This is only addressed in a few studies to a limited extent. Moreover, most of the studies mainly focus on fossil energy use and GHG emissions. In this paper, a case study is presented wherein a more complete set of impact categories is used. Land use has been left out of account as only hectare data would be given which is obviously dominated by agriculture. Moreover, different allocation methods are applied to assess the sensitivity of the outcomes for allocation choices.

Materials and methods This study focuses on the comparison of LCA results from the application of different allocation methods by presenting an LCA of gasoline and ethanol as fuels and with two types of blends of gasoline with ethanol, all used in a midsize car. As a main second-generation application growing fast in the USA, corn stover-based ethanol is chosen as a case study. The life cycles of the fuels include gasoline production, corn and stover agriculture, cellulosic ethanol production, blending ethanol with gasoline to produce E10 (10% of ethanol) and E85 (85% of ethanol), and finally the use of gasoline, E10, E85, and ethanol. In this study, a substantially broader set of eight environmental impacts is covered.

Results LCA results appear to be largely dependent on the allocation methods rendered. The level of abiotic depletion and ozone layer depletion decrease when replacing gasoline by ethanol fuels, irrespective of the allocation method applied, while the rest of the impacts except global warming potential are larger. The results show a reduction of global warming potential when mass/energy allocation is applied; in the case of economic allocation, it gives contrary results. In the expanded systems, global warming potential is significantly reduced comparing to the ones from the allocated systems. A contribution analysis shows that car driving, electricity use for cellulase enzyme production, and ethanol conversion contribute largely to global warming potential from the life cycle of ethanol fuels.

Discussion The reason why the results of global warming potential show a reverse trend is that the corn/stover allocation ratio shifts from 7.5 to 1.7 when shifting from economic allocation to mass/energy allocation. When mass/energy allocation is applied, both more credits (CO_2 uptake) and more penalties (N_2O emission) in agriculture are allocated to stover compared to the case of economic allocation. However, more CO_2 is taken up than N_2O (in CO_2 eq.) emitted. Hence, the smaller the allocation ratio is between corn and stover, the lower the share of the overall global warming emissions being allocated to ethanol will be. In the system expansion approach, global warming potentials are significantly reduced, resulting in the negative values in all cases. This implies that the system expansion results are comparable

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to one another because they make the same cutoffs but not really to the results related to mass, energy, and economic value-based allocated systems.

Conclusions The choice of the allocation methods is essential for the outcomes, especially for global warming potential in this case. The application of economic allocation leads to increased GWP when replacing gasoline by ethanol fuels, while reduction of GWP is achieved when mass/energy allocation is used as well as in the system where biogenic CO_2 is excluded. Ethanol fuels are better options than gasoline when abiotic depletion and ozone layer depletion are concerned. In terms of other environmental impacts, gasoline is a better option, mainly due to the emissions of nutrients and toxic substances connected with agriculture. A clear shift of problems can be detected: saving fossil fuels at the expense of emissions related to agriculture, with GHG benefits depending on allocation choices. The overall evaluation of these fuel options, therefore, depends very much on the importance attached to each impact category.

Recommendations and perspectives This study focuses only on corn stover-based ethanol as one case. Further studies may include other types of cellulosic feedstocks (i.e., switchgrass or wood), which require less intensive agricultural practice and may lead to better environmental performance of fuel ethanol. Furthermore, this study shows that widely used but different allocation methods determine outcomes of LCA studies on biofuels. This is an unacceptable situation from a societal point of view and a challenge from a scientific point of view. The results from applying just one allocation method are not sufficient for decision making. Comparison of different allocation methods is certainly of crucial importance. A broader approach beyond LCA for the analysis of biorefinery systems with regard to energy conservation, environmental impact, and cost–benefit will provide general indications on the sustainability of bio-based productions.

Keywords E10 · E85 · Allocation · Corn stover · Environmental impact · Fuel ethanol · Gasoline · System expansion

1 Background, aim, and scope

Facing the threat of oil depletion and climate change, the production and use of bioethanol from renewable resources as a fuel instead of gasoline has been strongly promoted on a global scale. Bioethanol, however, is connected to environmental problems of its own. Thus, the question is raised, what indeed the environmental benefits of bioethanol are and how to compare different fuel options from an environmental point of view. Several studies were conducted on the environmental impact of bioethanol, focusing particularly on two main aims behind the use of biofuels: life cycle fossil energy efficiency and greenhouse gas (GHG) emissions (Macedo 1998; Kim and Dale 2005a; von Blottnitz and Curran 2007; Zah et al. 2007; Gnansounou et al. 2008; Nguyen and Gheewala 2008; Liska et al. 2009). With respect to these two main aims, the use of bioethanol is not unchallenged. For instance, a review study was published in "Science" on the production of ethanol from corn (Farrell et al. 2006); this is a relevant case because of the tremendous scale of investment in the production of ethanol from corn in the USA. The study indicates that the replacement of crude oil appears to be rather effective (about 95%). However, the emission of greenhouse gases is diverging between the reviewed studies, ranging from 32% higher to 20% lower compared with the use of gasoline. In addition, criticism is expressed on the production of biofuels regarding land use requirements. This holds true particularly for the first generation of bioethanol, using the carbohydrates from dedicated crops like corn, wheat, sorghum, potato, sugar cane, sugar beet, cassava, etc. (Kim and Dale 2005a, b; Gnansounou et al. 2008; Halleux et al. 2008; Leng et al. 2008; Macedo 2008). Especially the land use requirements, causing competition with land for food and nature elsewhere, are the driving forces for the technology of second-generation bioethanol—which uses celluloses from low-value agricultural products or wastes, like corn stover, wheat straw, and bagasse from sugar cane, wood, or grass. Some studies have been performed on these new production routes (Fu et al. 2003; Sheehan et al. 2004; Kemppainen and Schonnard 2005; Spatari et al. 2005; Searcy and Flynn 2008; Luo et al. 2008; González-García et al. 2009). These studies show, to a varying degree, reduction of fossil fuel use and of GHG emissions, in comparison with the use of gasoline. Since the carbon dioxide (CO_2) uptake in agriculture is counteracted by the nitrous oxide (N_2O) emitted in agriculture and the CO_2 emissions generated in other parts of the life cycle, the reduction of GHG emissions depends on the greenhouse gases emitted in the whole chain, which may be substantial in relation to the emissions at final use.

However, the studies on both the first- and second-generation bioethanol raise a number of further questions. First of all, there is insufficient consistency regarding the definition of system boundaries. For instance, an ethanol system may be incomplete by not including the production of cellulase enzyme which is used to degrade cellulosic feedstock. Secondly, some questions can be raised with regard to the allocation methods used in these studies for the attribution of environmental impacts from processes

generating several other products as co-products. A high sensitivity to the allocation method has been reported for LCA results when evaluating carbon intensity and fossil energy consumption for bioethanol pathways (Kim and Dale 2002; Malça and Freire 2006; Beer and Grant 2007). However, these studies focus mostly on the first-generation feedstocks such as corn, wheat, and sugar beet, where allocation is less important to results. The environmental performances are not evaluated with more complete set of impact categories.

In the present study, corn stover-based fuel ethanol is investigated using LCA and compared with gasoline from fossil origins. The full life cycles of fuel ethanol and gasoline are analyzed, including the production, transport, and use of the raw materials, fuels, and electricity. Advanced technologies are assumed in both agriculture practice and ethanol refinery. The influence of different allocation methods on results is a core issue of this study. Whereas most case studies focus just on GHG emissions and resource depletion, in this case, a larger set of environmental impacts are included. The investigation of potential tradeoffs between impact categories is another main issue in this case study.

2 Methodology

LCA is a tool for the analysis of environmental impacts of a functional unit, taking into account the complete life cycle of a product (good or service) delivering the functional unit. It is, therefore, well suited to answer the question raised in the introduction, "how to compare different fuel options from an environmental point of view." Typically, LCA studies on one given topic do yield varying results due to differences in data and in methodological assumptions. In order to cope with this and to render studies better comparable, extensive efforts are undertaken in the LCA community to standardize assumptions and procedures and build up reference databases. However, in different situations, different approaches to modeling may apply; hence, explicit choices are always required.

The present study concerns the general comparison of technologies for the car driving function without specific local circumstances playing a role. For this purpose, the ISO 14040-44 series (2006), elaborated into methodological choices and procedures by Guinée et al. (2002), is followed.

2.1 Functional unit and alternatives

The functional unit in this study is defined as power to wheels for 1-km driving of a midsize car. In practice, ethanol is mainly used in one of two ways in vehicle fuel (Keller 1984; Homewood 1993): (1) blended with gasoline, typically 5–20% by volume, for use in existing vehicles with no engine modifications; (2) blended with gasoline, typically 85–100% by volume, for use in vehicles with specifically modified engines. In this study, ethanol is assumed to be used in both ways, as a mixture of 10% ethanol with 90% gasoline by volume (termed E10) and as a mixture of 85% ethanol with 15% gasoline by volume (termed E85). As a reference alternative, a hypothetical case of pure ethanol is also taken into account. Therefore, the fuel alternatives are gasoline, E10, E85, and ethanol, in amounts required to deliver the same amount of energy "to the wheels."

2.2 System boundary

All relevant processes are included within the boundary of the fuel systems, as shown in Fig. 1. Furthermore, those for capital goods and wastes management are included as well. The emissions and wastes associated with the production and disposal of the passenger car are outside of the system boundaries.

2.3 Data sources and software

Data used in this study are obtained from different sources. The US Life Cycle Inventory Database (http://www.nrel.gov/lci/) is the source for agriculture data. Data on the ethanol production process from corn stover are based on a detailed technical process design, using data from NREL (Aden et al. 2002). This production process can be characterized as "future technology": the design is not implemented at a significant scale yet and, therefore, may be on the optimistic side. Emissions from capital goods production are from the EIPRO database (Tukker et al. 2006). Gasoline production data are provided by Swiss Centre of Life Cycle Inventories (http://www.ecoinvent.org/). Emission data of car driving using gasoline, E10 and E85, are acquired from the reports on emission test of different fuels (Kelly et al. 1996; Reading et al. 2002). The completeness of data may differ between sources; therefore, one source, ecoinvent, is used when possible, as this source has a long learning experience and involves a very broad range of processes, around 2,630. Data gaps resulting from general data unavailability are filled by estimating based on a variety of assumptions as noted below. The software package Chain Management by Life Cycle Assessment (http://cml.leiden.edu/software/software-cmlca.html) is used for the analysis.

2.4 Key assumptions

In this study, the ethanol production plant is assumed to be located in the middle of the Corn Belt farmland, state of Iowa, midwest of the USA. The stover is assumed to

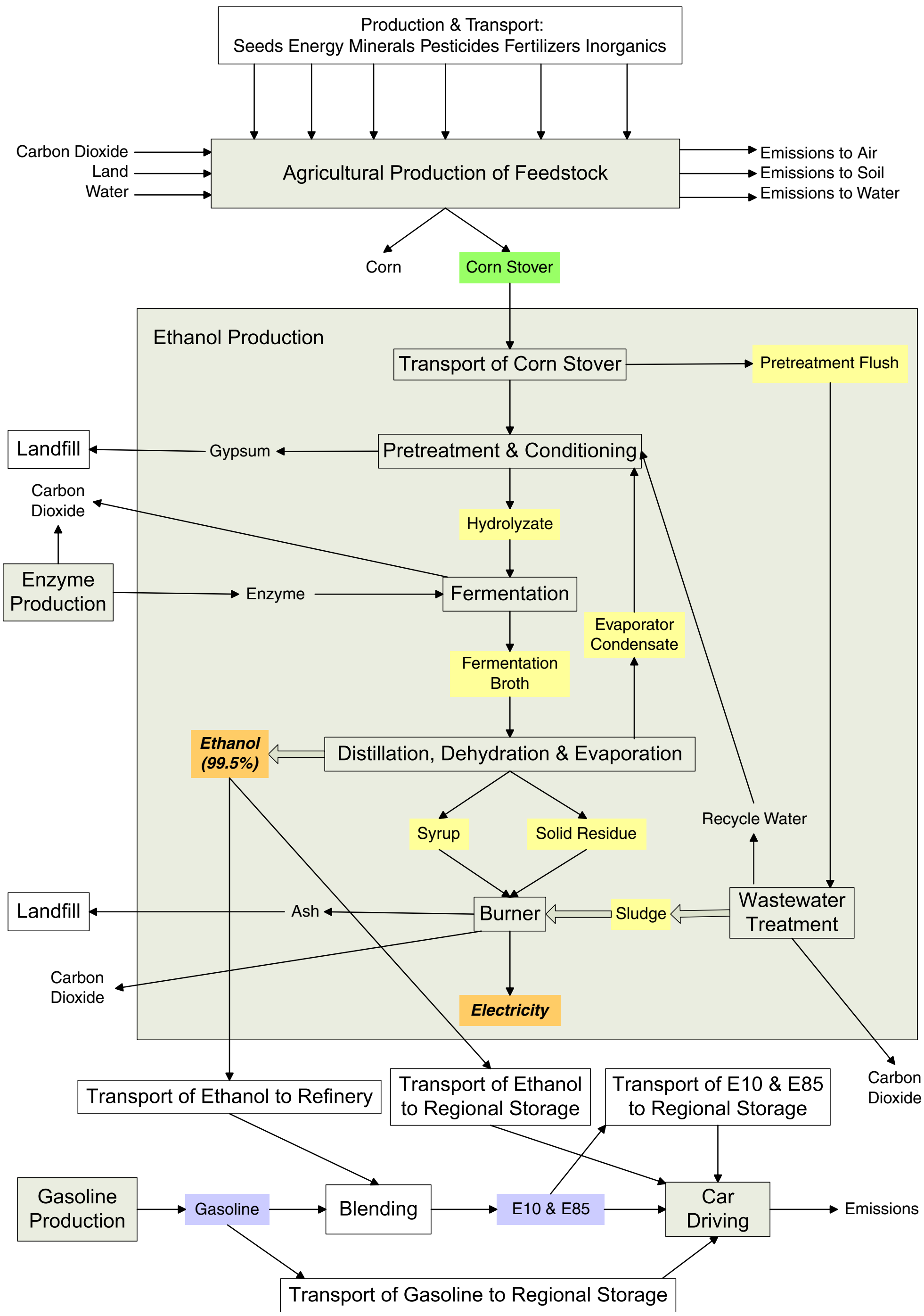

Fig. 1 The life cycle of ethanol from corn stover

be collected within an 80 km (50 miles) radius around the plant (Aden et al. 2002). Corn stover is transported by lorries with a load of 16 tonnes, and the transport of the rest of the materials and products is by road using lorries with a load of 32 tonnes. The average transport distance for the stover to the ethanol plant is derived from the above data, yielding a distance of 56 km (112 km both ways); 20 km is assumed to be the transport distance of ethanol to the refinery. For the distance between the refinery and the regional storage, the value from ecoinvent is followed (34 km). Therefore, for comparison, the transport distance of E10, E85, and ethanol to their regional storages is assumed to be 34 km. For gasoline, E10 and E85 emission data are based on a standard test procedure, covering a mix of driving on urban roads and on motorways. For ethanol, the emission data are estimated based on the assumption of driving with nearly 100% ethanol.

2.5 Allocation methodology

The allocation procedure in a multiproduct process is a most critical issue in LCA. The ISO 14040-44 series (2006) recommends avoiding allocation whenever possible either through subdivision of certain processes or by expanding the system limits to include the additional functions related to them. This was done in our case in the following manner:

- Assuming continuous corn production instead of crop rotation to avoid having to allocate over a variety of crops and their destinations; this assumption is not unrealistic
- Assuming the electricity produced from wastes is used in the ethanol refinery itself instead of being sold to the grid; this may not be fully according to reality
- Expanding the system to include the "corn for food and feed" as an additional function

If "avoiding" allocation is not possible, the ISO series recommends using methods that reflects the physical relationship such as mass and energy content or use other relevant variables to allocate, such as economic value of the products, which is similar to the cost allocation methods in managerial accounting (Guinée et al. 2004). We used energy and mass allocation as well as economic allocation in this case study. Regarding the allocation procedure, the following multiproduct processes were considered in the gasoline lifecycle: the refinery of crude oil to produce gasoline, diesel, and other co-products.

In the ethanol life cycle, multi-output processes are the following:

- Agricultural production, where both corn and stover are produced
- Ethanol production, where both ethanol and electricity are produced

For the gasoline production, the allocations were taken as currently implemented in the ecoinvent database by its designers. The ecoinvent default allocation includes differentiated allocation factors based on physical–causal relationships, common physical parameters (mass or heating values), and/or the economic values of the valuable outputs of the multi-output process, after processes have been split up in order to avoid allocation (Jungbluth et al. 2005). For ethanol from corn stover, allocation based on mass, energy content, and economic value was applied in addition to system expansion as described above. The mass ratio between stover and corn produced in agriculture is roughly 1:1 (Kim and Dale 2004), and the same is true for the energy content (Pordesimo et al. 2005). The prices of the collected stover and corn currently are \$0.033/kg (Graham et al. 2007) and \$0.148/kg (Ethanol Market 2007), respectively. However, in the current agriculture practice, only 28% of the stover is harvested (Graham et al. 2007), and the rest is left in the field for the soil fertility. Sheehan et al. (2002) stated that as much as 60% of the stover can be collected and converted to fuel ethanol. As the technologies assumed in the ethanol production are advanced, the value of 60% is taken by assuming advanced agriculture practice still leaving soil fertility intact. The carbon fixed in the non-harvested stover has been left out of account in the analysis. The results in the percentages of stover and corn for partitioning based on mass/energy and economic value are summarized in Table 1.

The system expansion approach was developed for the agricultural process in the system only. System expansion implies taking all the outputs of the multi-outputs process into the functional unit and adding products to make the total of functions equal among all the alternatives. In the ethanol system, corn (used for food and fodder) is produced besides stover (used for ethanol). Hence, the gasoline alternative needs to be expanded with the equivalent amount of food and fodder. We assumed this to be corn and stover again. As corn and stover are produced in the same agriculture process, the mixture with different amounts is assumed to fulfill the same function in all systems; the amount is estimated based on the nutritional values. The amount of ethanol for driving 1 km is produced by utilizing 0.393 kg of stover, while 0.655 kg of corn is produced in the agriculture. Hence, when driving with gasoline the functional unit is "1 km of driving +1.048 kg of corn and stover (total nutritional value 13.6 kJ)," while driving with ethanol 0.393 kg of additional biomass needs to be produced. The nutritional value of corn is 14.3 kJ/kg (Organic Facts 2009), and the one of stover is estimated to be 10.7 kJ/kg based on the composition difference in corn and stover. As corn has higher nutritional value, the total amount of biomass for food and fodder is less than 1.048 kg. For the case of E10 and E85, the method of estimation is applied. The functional unit used in all four alternatives is defined as "one kilometer of car driving + nutritional value 13.6 kJ of corn + stover," as illustrated in Table 2. The chains of corn and stover for food and fodder are not followed beyond the farm, which is considered sufficient for the comparative purpose of this study.

The co-produced electricity in the ethanol production is fully used in the system due to electricity requirement in

Table 1 Partitioning ratio for economic and mass/energy allocation

Allocation	Percentage	
	Stover (%)	Corn (%)
Economic value	11.8	88.2
Mass/energy content	37.5	62.5

Table 2 Function units of current system and added biomass for all fuel options

Alternative	Item				
	Current system			Added biomass	
	Fuel (kg)	Corn (kg)	Stover (kg)	Corn (kg)	Stover (kg)
Gasoline, corn, and stover	0.066	0.000	0.000	0.655	0.393
E10, corn, and stover	0.069	0.045	0.000	0.624	0.374
E85, corn, and stover	0.092	0.514	0.000	0.301	0.180
Ethanol, corn, and stover	0.099	0.655	0.000	0.203	0.122

enzyme production. Therefore, this case is considered as a closed loop, and allocation is unnecessary. In more general cases where these amounts differ, allocation cannot be resolved in this way: electricity delivered to the grid and taken from the grid has to be specified separately, and allocation choices will have to be made.

2.6 Impact assessment and interpretation

The following impact categories are included in this study:

- Abiotic depletion (ADP)
- Global warming potential (GWP)
- Ozone layer depletion (ODP)
- Photochemical oxidation (POCP)
- Human and ecotoxicity (HTP and ETP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)

We left “land use” out of account for two reasons. One is that land use shifts induced elsewhere do not fit into the LCA framework. This is a limitation that all LCA types of studies have by necessity due to the use of the functional unit instead of full totals in all markets concerned. At the LCA level, we could have included hectares of land use which would lead to obvious results—agriculture is dominant for the land use.

Weighting is not included in this study, as we want to show differences per impact category due to different allocation methods applied. A contribution analysis was performed in which the contributions of life cycle stages or groups of processes to the total result are examined, expressing the contribution as a percentage of the total. The major parts of the four main alternatives are agriculture production, enzyme production, ethanol production, gasoline production, and car driving.

3 Results and discussion

In this section, the results of the inventory analysis and impact assessment based on different allocation methods are presented, and the results of the contribution analysis are discussed.

3.1 LCA results

3.1.1 Mass, energy content, and economic value-based allocation

Figure 2 gives the overall results when applying allocation based on mass, energy content, and economic value between corn and stover as well as system expansion. In this case, mass and energy ratios between corn and stover are identical. It is worth noting that the function unit used in the system expansion approach is different from the ones in the allocation approaches.

The results show that the level of ADP and ODP are reduced when replacing gasoline by ethanol fuels irrespective of the allocation method applied. This is obviously due to the replacement of fossil resources by renewables—corn stover in this case. Crude oil, natural gas, and coal are the main contributors of the ADP level, while the ODP level is mainly contributed by the methane emission from the crude oil production onshore. In the case of economic allocation, the reduction is more significant due to the smaller share of agricultural emissions allocated to stover.

For the rest of the impact categories except GWP, applying ethanol fuels leads to worse environmental performance, also irrespective of the allocation method. When shifting from gasoline to ethanol fuels, the emissions causing POCP from natural gas production and oil exploitation decrease, but the ones from ethanol production contribute even more to POCP level. Moreover, agriculture contributes largely to human and ecotoxicity, acidification, and eutrophication due to the use of agrochemicals; thus, gasoline is a better option in terms of these impacts. The application of economic allocation leads to a better environmental performance on these impact categories because most of the agriculture related emissions are allocated away to corn, but still, gasoline is the better option.

The most interesting outcome in this study refers to GHG emissions. When mass and energy content-based allocation is applied, the GWP score is significantly better

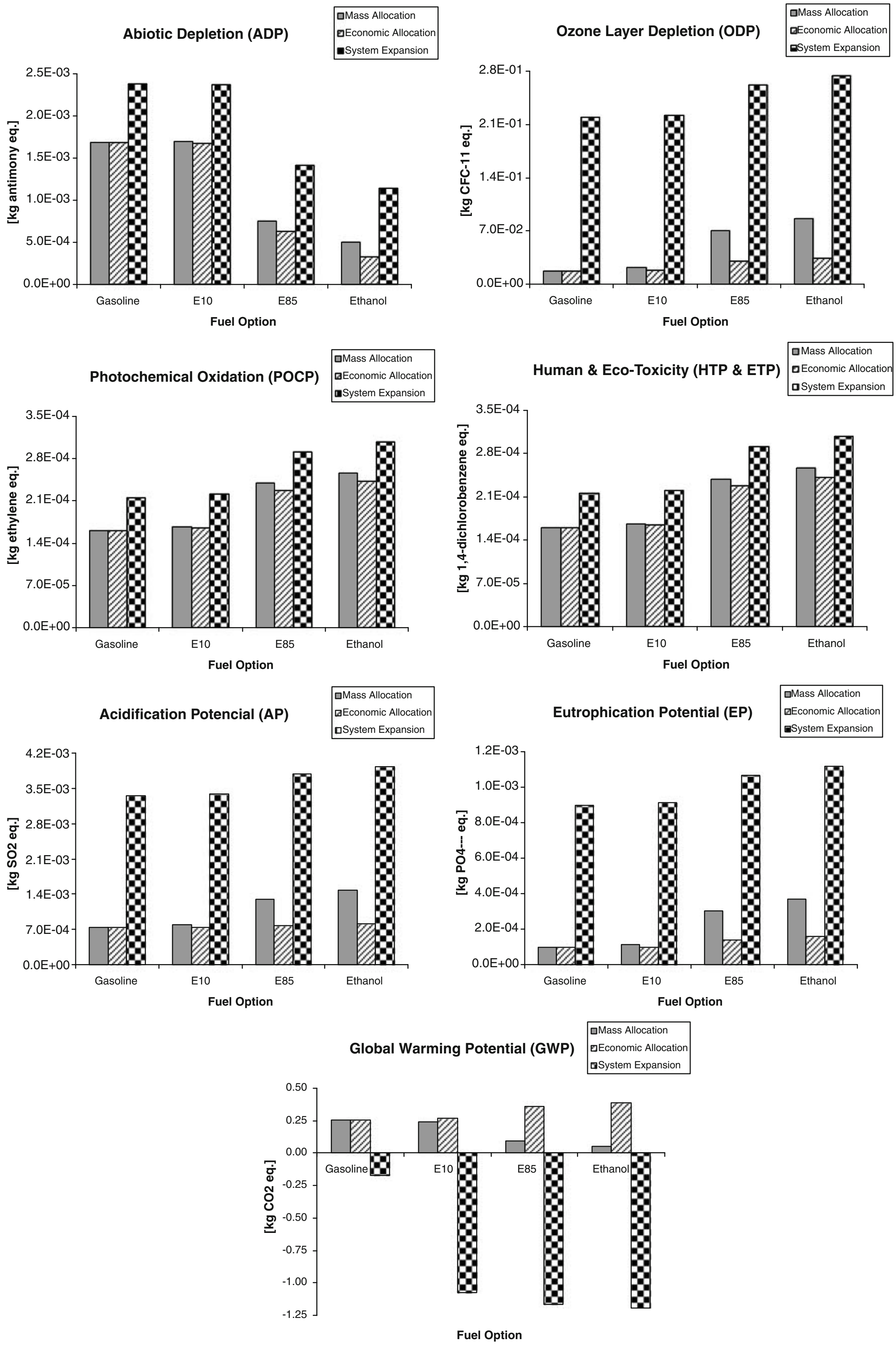

Fig. 2 Overall results of the environmental impact of all fuel options

for ethanol fuels compared to gasoline. The application of economic value-based allocation gives opposite results: now, the biofuels perform worse than gasoline. The reason is that the corn/stover ratio shifts from 1.7 to 7.5 when shifting mass/energy allocation to economic allocation. When mass/energy allocation is applied, both more credits (CO_2 uptake) and more penalties (N_2O emission) in agriculture are allocated to stover compared to the case of economic allocation. However, more CO_2 is taken up than N_2O (in CO_2 eq.) emitted. Hence, the smaller the allocation ratio between corn and stover, the less the GWP score for stover ethanol becomes. This finding shows that the outcomes are highly sensitive to the allocation method applied. Therefore, allocation issues are of crucial importance in LCA studies applied to biofuels and should be discussed explicitly in any such case study.

We have chosen in this case study to follow “normal” LCA procedure when dealing with CO_2 uptake and CO_2 emissions: the uptake counts as an extraction from the environment; therefore, the emissions of this biogenic CO_2 are counted just the same as CO_2 emissions from fossil sources. In the field of energy research, there is a custom of ignoring both CO_2 extractions from the atmosphere and emissions of biogenic CO_2. In a straightforward system that does not require allocation; the net result should be the same. However, when allocation is needed, this may no longer be the case. As the allocation methods applied strongly affect the results of GWP, a comparative computation of the system excluding biogenic CO_2 was made, and the result is given in Fig. 3. When biogenic CO_2 is excluded, the results show a reduction of GWP when replacing gasoline with ethanol fuels irrespective of the allocation method applied. What, in fact, has happened by excluding biogenic CO_2 is that CO_2 escapes the chosen method of allocation. Instead, CO_2 is allocated in all cases on the basis of the carbon balance of the chain. Implicitly, another way of allocation has entered the story and has been mixed with the other types of allocation. It is relevant to acknowledge this.

Further computations show that when the allocation ratio between stover and corn becomes 0.29:0.71, GWP of gasoline and ethanol (on basis of energy content in both fuels) are the same and, thus, also for all mixtures. This can be seen as a breakeven point, which means when the allocation ratio is higher than 0.29:0.71, GWP will decrease with increasing ethanol content. For this special case to result, the price of the stover has to increase to at least \$0.1/kg, three times higher than the current price of \$0.033/kg, while the price of corn remains the same. When the price of the stover reaches the one of corn, the results of the impact assessment will be the same as the current results with mass/energy-based allocation applied in agriculture. Nevertheless, the price will be largely dependent on the US policy on biofuels.

3.1.2 System expansion

It is worth noting that the functional unit defined in this approach does not only comprise one kilometer of car driving but also the same amount of energy in the added

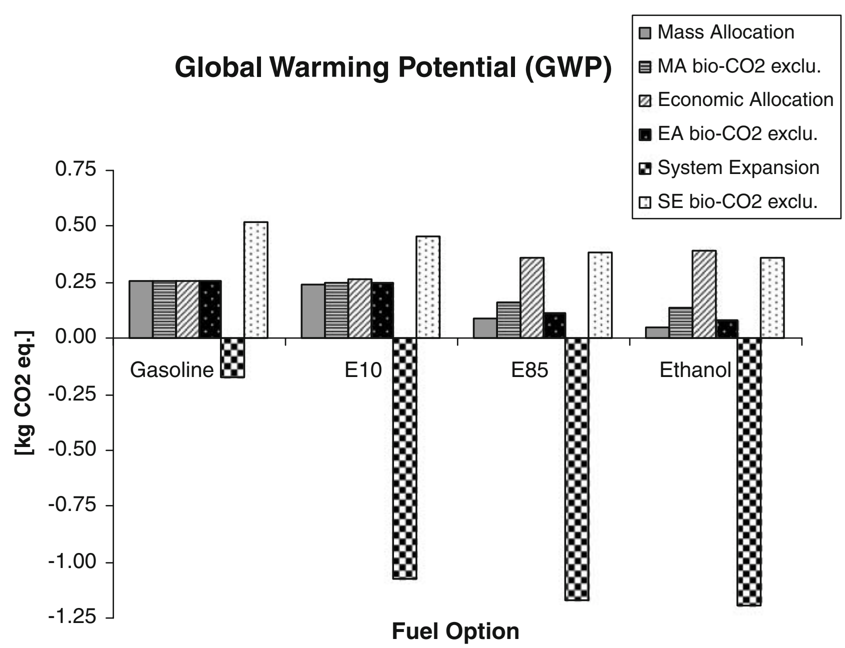

Fig. 3 Comparative results of global warming in all cases

food and fodder in all the alternatives, as described in the "Methodology" section. These additional products lead to substantially larger environmental impact than outcomes given above. The results are shown in Fig. 3 in comparison with other approaches.

The levels of all impact categories except GWP are higher in the expanded systems than the allocated systems when replacing gasoline by ethanol. The reason for this is that in the other approaches, only the life cycles of the fuels are taken into account, while in the system expansion approach, the functional unit does not only include 1-km driving but also additional agricultural production of food and stover. The CO_2 taken by the growth of food and fodder are ultimately released to the atmosphere, but that does not show since the system only includes the co-production of food and fodder, not the downstream of food and fodder digestion. Thus, global warming potential are significantly reduced, resulting in the negative values in all cases. This implies that the system expansion results are comparable to one another because they make the same cutoffs but not really to the results related to mass, energy, and economic value-allocated systems.

3.2 Contribution analysis

A contribution analysis was conducted to identify the major subprocesses which contribute significantly to the environmental impact of the total system. This can be done for all the impact categories; however, here, only the results of global warming potential using economic value-based allocation are shown as an example (Fig. 4).

In the gasoline life cycle, car driving (82%) is the main contributor to GWP. In the life cycle of E10, the contributions of fossil resource extraction (7%), CO_2 uptake (–5%), electricity generation (6%), and fermentation (2%) are also shown up in the figure. In the life cycle of E85 and ethanol, the results of the contribution analysis are similar but, of course, stronger. Besides CO_2 uptake, electricity generation is the largest contributor due to the large electricity use in enzyme production. Figure 3 also shows the significant contributions of car driving, fermentation, N_2O emissions from agriculture, and fossil fuel use to GWP. The contribution analysis indicates that the bottlenecks are N_2O emissions from agriculture, enzyme production, and electricity generation in the ethanol refinery.

The emissions from the production of capital goods do not seem to be important. The results show little difference from the ones not including the emissions from the capital goods production in ethanol process.

4 Conclusions

The levels of abiotic depletion and ozone layer depletion decrease when shifting from gasoline to ethanol fuels, irrespective of the allocation method applied, only the degree of reduction is different; while the levels of photochemical oxidation, human and ecotoxicity, acidification, and eutrophication potential increase in all cases. Here, we may conclude a clear case of problem shifting: solving one problem (oil depletion) at the expense of increasing others (agriculture-related emissions).

The choice of the allocation methodology is essential for the outcomes related to GHG emissions. Since this is an important issue and one of the main reasons for considering biofuels instead of fossil fuels, it is important to realize this

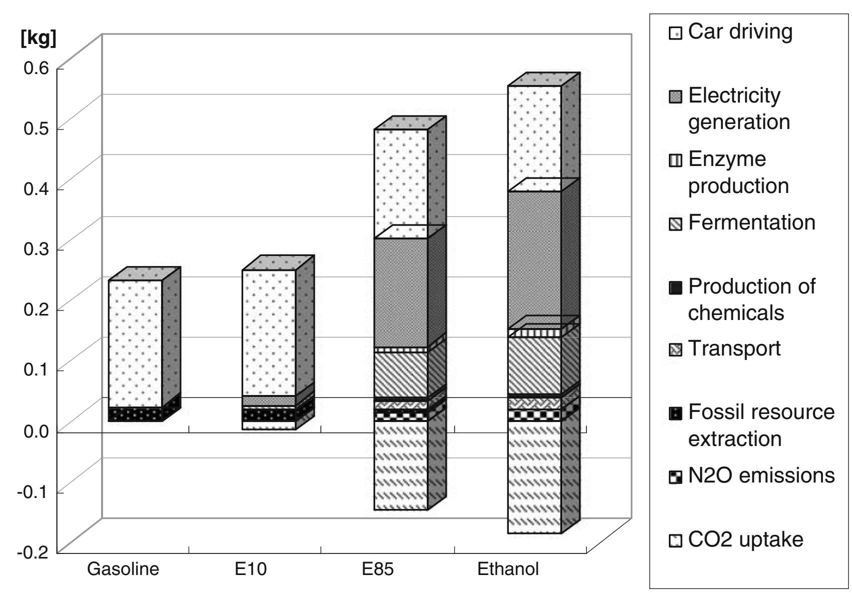

Fig. 4 Contributions of the main process to global warming potential (economic value-based allocation)

and give allocation a special place in life-cycle-based studies of biofuels. Subsequent replacement of gasoline by ethanol increases global warming potential when economic allocation is applied based on current prices. In contrast, reduction of global warming potential is achieved when mass/energy allocation is applied. In the agricultural production, carbon dioxide is taken up for the growth of corn and stover, and global warming potential are caused mainly by nitrous oxide released from the soil. When economic value-based allocation is applied, both less credits (CO_2 uptake) and less penalties (N_2O emission) are allocated to stover comparing to the case of mass/energy-based allocation. However, more CO_2 is taken up in the agriculture than N_2O (in kg CO_2 eq.) emitted which results in the increment of global warming potential. When biogenic CO_2 is altogether excluded from the system, as is customary in energy analysis studies of biofuels, a reduction of GWP is achieved irrespective of the allocation method applied. However, it is important to notice that by doing this, in fact, a different allocation method has entered (allocation based on C balance) and is mixed with the other allocation methods.

In expanded systems where both driving, food, and fodder production are taken into account, all the environmental impacts except global warming potential are larger than the ones in allocated systems when replacing gasoline by ethanol. The negative global warming potential is mainly due to the carbon dioxide uptake in the agriculture. In terms of abiotic depletion, global warming potential, and ozone layer depletion, ethanol fuels have better environmental performance than gasoline; however, gasoline is a better fuel when the rest of the impacts are concerned. The overall evaluation depends on the importance attached to each impact category.

If larger cellulosic ethanol markets can be established in the USA with a higher price for stover as feedstock, the ratio of economic allocation will shift towards the one of mass/energy allocation. If this situation is reached, a replacement of gasoline by ethanol will consistently show an increasing reduction of global warming potential irrespective of the allocation method applied.

GHG emissions in agriculture are, besides biogenic CO_2 uptake and emissions, largely determined by the emission of nitrous oxide. In the ethanol production process, GHG emissions are mainly due to electricity generation and fermentation. The production of the enzyme used for hydrolysis requires a substantial amount of electricity for air compression. The production of this electricity, either from fossil resources or combustion of wastes in the plant, also generates a considerable amount of CO_2 emission in the chain. The main bottleneck processes in the chain are nitrous oxide emissions in agriculture and electricity use required in enzymes production for ethanol production; these two processes should, therefore, receive most attention when focusing on improving the GHG performance of the chain.

We now have three allocation methods which can be applied and are applied in the environmental analysis of biofuels: (1) mass/energy-based allocation, (2) economic value-based allocation, and (3) system expansion. These can be combined with what is usual in many studies—leaving biogenic carbon out of the analysis. These lead to opposing outcomes for scores on climate change and to diverging outcomes on the most other environmental impacts.

5 Recommendations and perspectives

This study shows corn and stover agriculture is an intensive process. The production of other types of cellulosic feedstock may have a less intensive agricultural management. Further analysis should focus on different feedstock for the second generation bioethanol production such as sugarcane-bagasse, switch grass, wood and cassava, etc.

The outcomes are highly sensitive to the allocation methods applied, especially with regard to global warming, one of the main reasons to consider biofuels. This is unacceptable from a societal point of view and a challenge from a scientific point of view. Nevertheless, this has not yet raised the awareness of many decision makers who use LCA as a support tool. The results from applying one allocation method are certainly not sufficient in this case and may be in many other cases in the cellulosic ethanol LCA. It is relevant to notice that the so far uncontested practice of ignoring biogenic CO_2 in the chain is, in fact, another allocation choice: allocation based on the C balance. It is important that LCA practitioners realize this and deal with it in an appropriate manner. Mixing allocation methods in one case study is not advisable.

It is also advisable to broaden the attention to include more issues than GHG emissions, energy balance, and fossil fuel depletion in studies on biofuels. This study has shown that there is a clear shifting of problems from oil depletion toward eutrophication and toxicity due to the use of agrochemicals. The use of land and water has not been included in this study but here, too, important problem displacement issues may occur. In considering the sustainability of biofuel chains, this broader perspective must not be ignored.

LCA, as it stands, has its limitations not only in allocation issues but also in variable multi-input multi-output systems, such as complex biorefineries. A broader approach beyond LCA for the analysis of biorefinery systems with regards to energy conservation, environmental impact, and cost–benefit will provide general indications on the sustainability of bio-based productions.

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